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Modelling the distribution of wood properties along the stems of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) as affected by silvicultural management

Veli-Pekka Ikonen [a,*], Heli Peltola [a], Lars Wilhelmsson [b], Antti Kilpeläinen [a], Hannu Väisänen [a], Tuula Nuutinen [c], Seppo Kellomäki [a]

[a] University of Joensuu, Faculty of Forest Sciences, P.O. Box 111, FI-80101 Joensuu, Finland
[b] Skogforsk, The Forestry Research Institute of Sweden, Uppsala Science Park, S-751 83 Uppsala, Sweden
[c] The Finnish Forest Research Institute, Joensuu Research Unit, P.O. Box 68, FI-80101 Joensuu, Finland

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ABSTRACT

In this work, empirical ring-based models were developed to predict the distribution of early wood percentage, wood density and fibre length along the stems of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) as affected by silvicultural management. The performance of the ring-based models was also compared for Scots pine and Norway spruce with corresponding disc-based (cross-sectional) models. Moreover, both models were integrated with example simulations by a process-based growth and yield model to analyze how management, such as thinning, affects the growth and wood properties of Scots pine trees over a rotation as an average for the tree stem, but also along the stem.

The ring-based models built for annual early wood percentage (explained by ring width), air dry wood density (explained by early wood percentage and cambial age) and fibre length (explained by radial growth percentage and cambial age) predicted reasonably well the wood properties both at an intra-ring level, but also at a cross-sectional level. These predictions were also reasonably well in line with corresponding cross-sectional predictions by the disc-based models (which predicted the properties based on the number of annual rings and diameter at breast height and/or the cross-section being considered and temperature sum). The example simulations also demonstrated that both models predicted slightly lower wood density for dominant trees compared to dominated ones grown in thinned and unthinned Scots pine stands over a rotation. Unlike the disc-based model, the ring-based model predicted, on average, higher early wood percentage in dominant trees than in dominated ones. However, fibre length was not significantly affected when the averages of the whole stems were predicted, and this held true for both ring- and disc-based models.

In summary, the incorporation of empirical ring-based wood property models into a process-based growth and yield model, offers a means to study in detail how environmental conditions, forest structure and management affect the quantity and properties of stem wood produced over a rotation. The disc-based wood property models used in this work are based on data with large geographical and genetic variation, and therefore may turn out to be more applicable for predicting future wood and fibre resources at a regional and national level. This kind of integrated use of wood property models with a process-based growth and yield model could help us to evaluate the forest resources under current and changing climate.

1. Introduction

Silvicultural management affects the growth and yield and the consequent stem and wood properties of different genotypes through interactions between biological processes (e.g. height growth, radial growth of the stem and crown development) and environmental conditions (e.g. temperature, precipitation, nutri-

* Corresponding author. Tel.: +358 13 251 4401; fax: +358 13 251 4444.
E-mail addresses: veli-pekka.ikonen@joensuu.fi (V.-P. Ikonen), heli.peltola@joensuu.fi (H. Peltola), lars.wilhelmsson@skogforsk.se (L. Wilhelmsson), antti.kilpelainen@joensuu.fi (A. Kilpeläinen), hannu.vaisanen@joensuu.fi (H. Väisänen), tuula.nuutinen@metla.fi (T. Nuutinen), seppo.kellomaki@joensuu.fi (S. Kellomäki).

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ents and light). Correspondingly, the stem and wood properties of trees affect the suitability of wood as a raw material for mechanical wood processing and the quality of the end products. The wood and fibre properties also affect the processing as well as the quality and quantity of the pulp and paper and other forest-based products produced. In the forest industry, where even small changes in the material properties of wood may be extremely important, proper information on material properties of raw material would potentially allow the selection of the raw material for its most suitable purposes. Therefore, there exists a need for a deeper understanding of how environmental factors, forest structure and management affect the growth of trees within a stand and consequently the material properties of the stem and wood.

Silvicultural management such as the selection of tree species and genotype, spacing, thinning type and its intensity and fertilization are known to affect the growth and formation of wood properties of tree stands by changing the growth rate of the trees within stands. Competition for light tends to modify the allocation of growth along the stem, whereas competition for water and/or nutrients affects the overall growth rate (Cannell et al., 1984; Nilsson and Gemmel, 1993; Nilsson, 1994). Management, such as thinning, increases the living space of individual trees, resulting in faster growth and wider annual rings, having implications also for, e.g. wood density, early wood content and fibre properties. This is because wood properties are linked with the distribution of growth over the stem (Hakkila, 1966; Uusvaara, 1974; Saikku, 1975). However, the magnitude of the effect may vary depending on tree species, type (from above or from below) and intensity of thinning, the length of interval between thinnings, the position of the tree in the stand (dominant, intermediate or suppressed) and the cambial age (i.e. especially the phase of forming juvenile or mature wood) (Olesen, 1977; Moschler et al., 1989; Duchesne et al., 1997; Tasissa and Burkhart, 1998; Pape, 1999a,b; Wilhelmsson et al., 2000; Mörling, 2002; Jaakkola et al., 2005a,b; Peltola et al., 2007).

In recent years, interest in models that could predict growth and yield, but also stem and wood properties, has increased and led to the development of various models, e.g. empirical models for timber properties (Leban et al., 1996; Tian and Cown, 1996; Kellomäki et al., 1999; Moberg, 2000, 2001; Ikonen et al., 2003; Kantola et al., 2007). Similarly, models predicting average wood and fibre properties (e.g. wood density, late-wood percentage and fibre length) for cross-sections along the stems of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) have been developed by Wilhelmsson et al. (2002) and Ekenstedt et al. (2003). These models are based on input variables such as number of rings, diameter of stem cross-sections and average climate conditions during growth, expressed by estimated temperature sum according to Morén and Perttu (1994). The models were developed for characterisation of wood and fibre properties of different assortments, type of stands, trees and logs within stems before, during and after harvesting operations. In these models, the most important previously known sources of variation were considered to be geographical location (latitude and altitude), site fertility, inter-tree competition, cambial ages along stems, and genetic variation between individuals (Wilhelmsson et al., 2002). The primary goal with these disc-based models (predicting cross-sectional averages) has been to improve efficiency and give added value in industrial wood supply chains by proper selection of wood and fibres for different purposes.

On the other hand, process-based growth and yield models, developed in recent years, have also several strengths. They start from processes such as photosynthesis, use weather and soil data and different tree cohorts in a stand as inputs for simulations and could, thus, predict the growth and dynamics of tree stands over a rotation as controlled by environmental conditions and management (Kellomäki and Väisänen, 1997; Matala et al., 2003). By relating annual growth to the intra-ring wood properties, they could also offer useful tools to analyze how a selected genotype in interaction with changing environmental conditions (soil and climate) and management (e.g. spacing, thinning and fertilization) affect tree growth within a stand (dominant, co-dominant and suppressed) and the development of stem and wood properties over the trees' life-span.

In this work, empirical ring-based models were developed to predict the distribution of early wood percentage, wood density and fibre length along the stems of Scots pine and Norway spruce as affected by silvicultural management. In the above context, the performance of the ring-based models was analyzed and compared with the corresponding disc-based (cross-sectional) models presented by Wilhelmsson et al. (2002) and Ekenstedt et al. (2003). The model comparison was based on use of Finnish datasets (same as used in development of ring-based models for different properties) and independent Swedish validation dataset (for wood density). Moreover, both ring- and disc-based models were integrated for Scots pine with example simulations by a process-based growth and yield model (FinnFor) to analyze how management, such as thinning, affects the growth and wood properties of Scots pine stems (e.g. in dominant and dominated trees) over a rotation as an average, but also along the stem (e.g. inner part, outer part and top part).

2. Materials and methods

2.1. Development of ring-based properties models

2.1.1. Empirical datasets measured for model development

Various datasets were collected in Eastern Finland (close to Mekrijärvi Research Station, University of Joensuu, 62°47′N, 30°58′E, 145 m a.s.l.) for the development of ring-based models for early wood percentage, wood density (air dry) and fibre length in Scots pine and Norway spruce (Tables 1 and 2). The first Scots pine dataset originated from a long-term early thinning experiment established in the summer of 1986 in a naturally regenerated stand of Scots pine (ca. 40-year old) growing on a site with a rather low nitrogen supply (*Vaccinium* type). The second set of Scots pine data originated from a mature (90-year old, ca. 900 stems ha^{-1}) Scots pine dominated stand containing a 20% mixture of Norway spruce growing on a site with a medium fertility (*Myrtillus* type). The Norway spruce dataset originated from a Norway spruce dominated mature stand (about 80–90-year old, ca. 800 stems ha^{-1}) grown on a similar site as the Scots pine trees included in the second Scots pine dataset. These datasets consisted of sample discs taken at various tree heights from breast height to canopy top (Table 2), totalling 337 discs for Scots

Table 1
Numbers and averages from harvested sample trees of Scots pine and Norway spruce in Eastern Finland

Tree species	Total number of trees	Tree height (m)	Dbh (cm)	Number of rings at breast height	Total number of discs
Scots pine	136	14.0 (*10.2–24.0*)	9.5 (*4.1–27.6*)	30 (*18–83*)	337
Norway spruce	20	17.9 (*11.3–24.1*)	21 (*11.3–29.5*)	63 (*19–95*)	81

Range of variables given by italics.